PeV Cosmic Ray acceleration in the supernova post breakout expansion phase: kinetic-magnetohydrodynamic simulations

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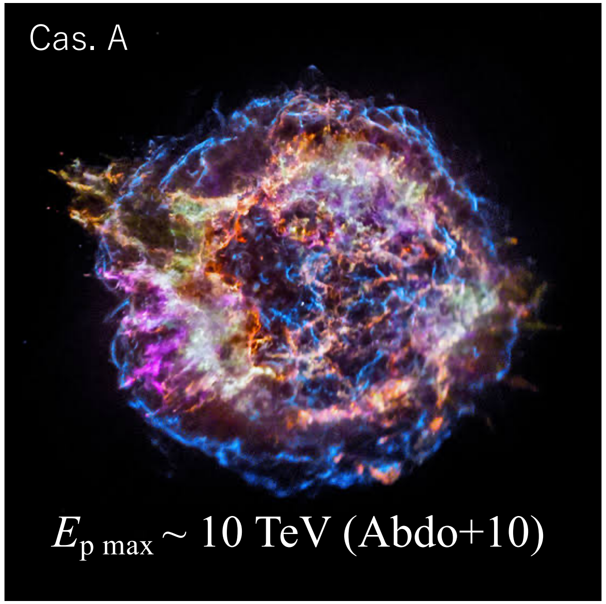
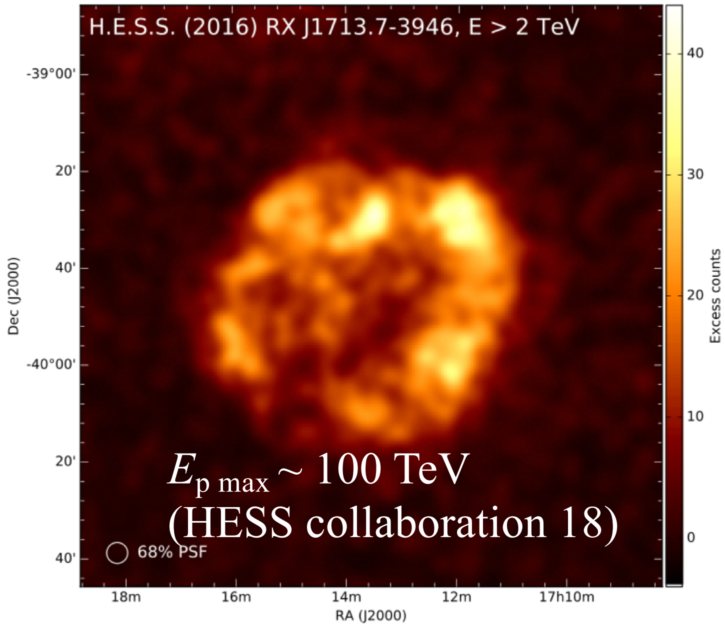
SNR as Candidate of PeVatron

Observations suggest that young SNRs ($t_{age} \sim 10^3$ yr) are not PeVatron.

✓ B filed amplification by the Bell instability is not enough?





Earlier phase of supernova shock in dense CSM is more plausible?

Schure & Bell 13, Marcowith+18

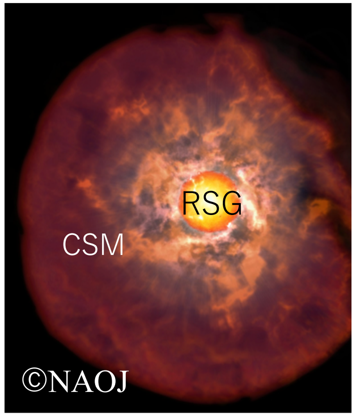
✓ High B field is expected in CSM created by red-super-giant, although B field amplification by the Bell instability is necessary.

✓ ~ 10 days after explosion as candidate of PeVatron.

Very Young SNRs as PeVatron Candidates

Schure & Bell 13; Marcowith+14, 18; Cardillo+15

RSG CSM model (Marcowith+18):



Wind kinetic energy density:

$$\varepsilon_K = \frac{1}{2}\rho_w v_w^2 = 5\times 10^{-3}\ \mathrm{erg\ cm^{-3}\ s^{-1}} \left(\frac{r}{10^{14} cm}\right)^{-2} \left(\frac{\dot{M}}{10^{-5}\ M_s/yr}\right) \left(\frac{v_w}{10\ km/s}\right)$$

Assuming K to B energy conversion efficiency ϖ

$$B_{\mathrm{CSM}} = (8\pi\ \varpi\varepsilon_K)^{1/2} = 0.25\ \varpi^{1/2}\ \mathrm{Gauss} \left(\frac{r}{10^{14} cm}\right)^{-1} \left(\frac{\dot{M}}{10^{-5}\ M_s/yr}\right)^{1/2} \left(\frac{v_w}{10\ km/s}\right)^{1/2}$$

* RSG wind is driven by pulsation of star that can naturally drive turbulent dynamo in the wind.

* If (turbulent) dynamo in the wind is very efficient, ϖ can be ~ 1 (Cho+).

* Zeeman observations report ~1 Gauss fields ($\varpi \sim 1$; Aurière+10, Tessore+17).

✓ E_{max} estimated from standard DSA (no B-field amplification assumed):

$$E_{max} \sim 10^{14}\ \mathrm{eV} \left(\frac{B}{0.1\ G}\right) \left(\frac{v_{sh}}{10^4 km/s}\right)^2 \left(\frac{t}{10\ day}\right)$$

→ 10 times B amplification is enough to achieve PeV acceleration.

Basic Equations

Bell+ 13
Inoue 19

Bell MHD + Telegrapher-type Diffusion Convection Eq.

E.o.C.: $\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho\, v_x) = 0,$

E.o.M.: $\frac{\partial}{\partial t}(\rho\, v_x) + \frac{\partial}{\partial x}\left(\rho\, v_x^2 + p + \frac{B_y^2 + B_z^2}{8\,\pi}\right) = 0$

$$\frac{\partial}{\partial t}(\rho\, v_y) + \frac{\partial}{\partial x}\left(\rho\, v_x\, v_y - \frac{B_x\, B_y}{4\pi}\right) = -\frac{1}{c} j_x^{(\mathrm{ret})}\, B_z \qquad \frac{\partial}{\partial t}(\rho\, v_z) + \frac{\partial}{\partial x}\left(\rho\, v_x\, v_z - \frac{B_x\, B_z}{4\pi}\right) = \frac{1}{c} j_x^{(\mathrm{ret})}\, B_y$$

E.E.: $\frac{\partial \epsilon}{\partial t} + \frac{\partial}{\partial x}\left\{v_x\left(\epsilon + p + \frac{B_y^2 + B_z^2}{8\,\pi}\right) - B_x \frac{(B_y\, v_y + B_z\, v_z)}{4\,\pi}\right\} = \frac{1}{c} j_x^{(\mathrm{ret})}(v_z B_y - v_y B_z) \qquad \epsilon = \frac{p}{\gamma - 1} + \frac{1}{2}\rho\, v^2 + \frac{B_y^2 + B_z^2}{8\pi}$

I.E.: $\frac{\partial B_y}{\partial t} = \frac{\partial}{\partial x}(B_x\, v_y - B_y\, v_x) \qquad \frac{\partial B_z}{\partial t} = \frac{\partial}{\partial x}(B_x\, v_z - B_z\, v_x)$

anisotropic component ∝ spectral current density j_{p}

Injection at shock front + cooling by p-p collision.

CR momentum distribution function: $f(x, \boldsymbol{p}) = f_0(x, p) + (p_x/p) f_1(x, p)$

Boltzmann eq. for f_0: $\frac{\partial F_0(x, p)}{\partial t} + \frac{\partial}{\partial x}(v_x\, F_0(x, p)) - \frac{1}{3}\frac{\partial\, v_x}{\partial x}\frac{\partial\, F_0(x, p)}{\partial \ln p} = -\frac{c}{3}\frac{\partial\, F_1(x, p)}{\partial x} + Q(x, p)$

for f_1: $\frac{\partial F_1(x, p)}{\partial t} + \frac{\partial}{\partial x}(v_x\, F_1(x, p)) = -c\frac{\partial\, F_0(x, p)}{\partial x} - \frac{c^2}{3\,\kappa(p, \boldsymbol{B})} F_1(x, p)$

where $F = f p^3$

Take limit $c \to \infty$ recovers conventional diffusion convection equation (Skilling 75).

We solve polar coordinate version of the equations.

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$\frac{\partial}{\partial t}(\rho\, v_y) + \frac{\partial}{\partial x}\Big(\rho\, v_x\, v_y - \frac{B_x \ldots}{4 \ldots}$

E.E.: $\frac{\partial\, \epsilon}{\partial t} + \frac{\partial}{\partial x}\Big\{v_x\Big(\epsilon + p + \frac{B_y^2}{\ldots}$ … B_z^2

I.E.: $\frac{\partial\, B_y}{\partial t} = \frac{\partial}{\partial x}(B_x\, v_y - B_y\, v_x)$

when $c \rightarrow \infty$, $F_1 \approx -\frac{3\,\kappa}{c}\frac{\partial\, F_0}{\partial x}$.

$-\frac{c}{3}\frac{\partial\, F_1}{\partial x} \approx \kappa \frac{\partial^2 F_1}{\partial x^2}$ diffusion term is recovered

CR momentum distributi…

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…ion.

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A Bit More Information of Microphysics

Return current estimation (Bell 04)

$$j^{(\mathrm{CR})}(r) = e\int_{p_1}^{\infty} v_{CR,r}\, f(r)\, 4\pi p^2 dp \cong e\int_{p_1}^{\infty} \frac{c}{3}\, f_1(r)\, 4\pi p^2 dp$$

p_1 is taken so that only CRs whose gyro-radius is larger than the Bell instability scale contribute to the current: $r_g(p_1) = \lambda_{\mathrm{Bell}}\left(= \frac{cB_r}{j^{(CR)}}\right)$

Diffusion coefficient (Caprioli & Spitkovsky 14)

$$\kappa(p, \vec{B}) = \frac{4}{3\pi}\frac{\max(B_r^2, \delta B^2)}{\delta B^2}\frac{v_{CR} p_{CR} c}{e\,\max(|B_r|, \delta B)}$$

When $\delta B/B < 1$, diffusion coefficient due to gyro-resonance scattering.

When $\delta B/B > 1$, Bohm diffusion under amplified B field.

Injection from thermal pool (Blasi+05)

Fraction η of shock heated gas put into acceleration process.

$$\left.\frac{\partial}{\partial t} f_0(t, r = r_{sh})\right|_{source} = \frac{\eta\, n\, v_{sh}}{4\pi\, p_{TeV}^2}\frac{p_{inj}}{p_{TeV}}\delta(p - p_{TeV})\delta(r - r_{sh})$$

* We assume CRs of E < 1TeV follows standard DSA spectrum at shock.

* Momentum space p=(1TeV/c to 10PeV) is expressed by 64 cells by logarithmic interval.

Difficulty of Direct Simulation

(ordinary) Diffusion convection equation has to solve a parabolic term

$\frac{\partial f}{\partial t} = \kappa \frac{\partial^2 f}{\partial x^2}$ → $\Delta t < \frac{\Delta x^2}{2\kappa}$ for numerical stability.

- the most unstable scale of the Bell instability is $L_{\mathrm{Bell}} \sim 10^{10}$ cm $\quad (\sim c\rho v_{\mathrm{A}} / j_{CR} B)$

  → $\Delta x < L_{\mathrm{Bell}}/10 \sim 10^9$ cm, while $L_{\mathrm{CSM}} \sim 10^{15}$ cm → $N_{\mathrm{cell}} > 10^6$

- If we use explicit scheme, the required timestep for stability becomes

$$\Delta t < \frac{\Delta x^2}{2\kappa} \sim 10^{-10}\ \mathrm{day}$$ (for PeV CRs)

→ need $>10^{11}$ timestep to integrate 10 days (impossible job).

* Implicit scheme can be used, but inconvenient for parallel computer (fatal problem).

Telegrapher-type modification (hyperbolic eqs) alleviate the problem!

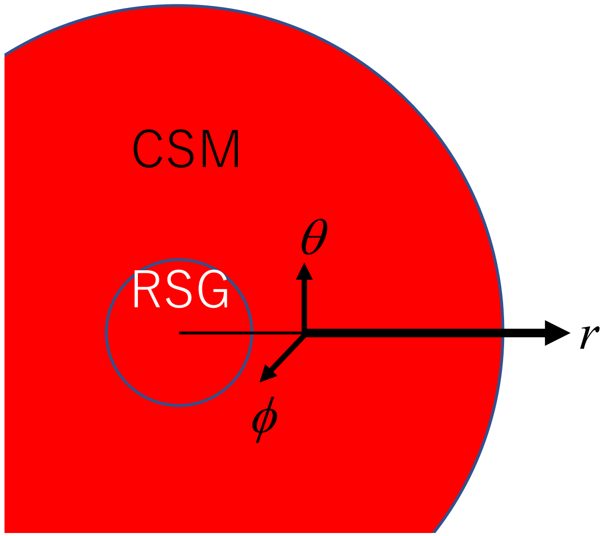
- Our telegrapher-type basic equations are hyperbolic.
- The CFL condition for hyperbolic eqs.:

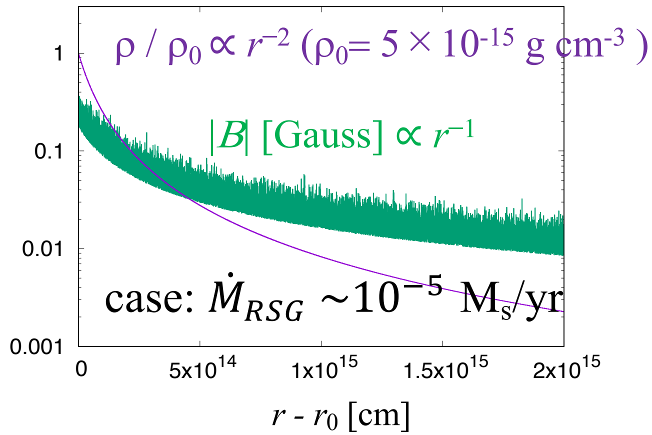
$$\Delta t < \frac{\Delta x}{c/\sqrt{3}} \sim 10^{-6}\ \mathrm{day} \quad (\text{for } \Delta x = L_{\mathrm{Bell}}/10)$$

→ 10^7 timestep for 10 days simulation (Feasible job).

Setting of Simulation

Blast wave simulation with CR acceleration and the Bell instability.





- ✓ $v_{\mathrm{shock}} \sim v_{\mathrm{ejecta}} = 10^4$ km/s ($M_s \sim M_A \sim 100$)
- ✓ Integrate from $r_0 = 10^{14}$ cm.

  * CSM in $r < r_0$ is too dense to accelerate particles due to inelastic pp-collision.

- ✓ Initial B field is turbulent (flat spectrum; typical of dynamo).

$$B_r(r, t{=}0) = B_{\mathrm{CSM}}(r)/\sqrt{2},\ \ |B_{\theta,\phi}(r, t{=}0)| = B_{\mathrm{CSM}}(r)/\sqrt{2}$$

- ✓ Injection rate: $\eta = 6 \times 10^{-4}$ → $P_{\mathrm{CR}}/\rho v_{\mathrm{sh}}^2 \sim 0.1$

  consistent with observational constraint from SN1997J:
  $\eta < 10^{-3}$ (Tatischeff 09).

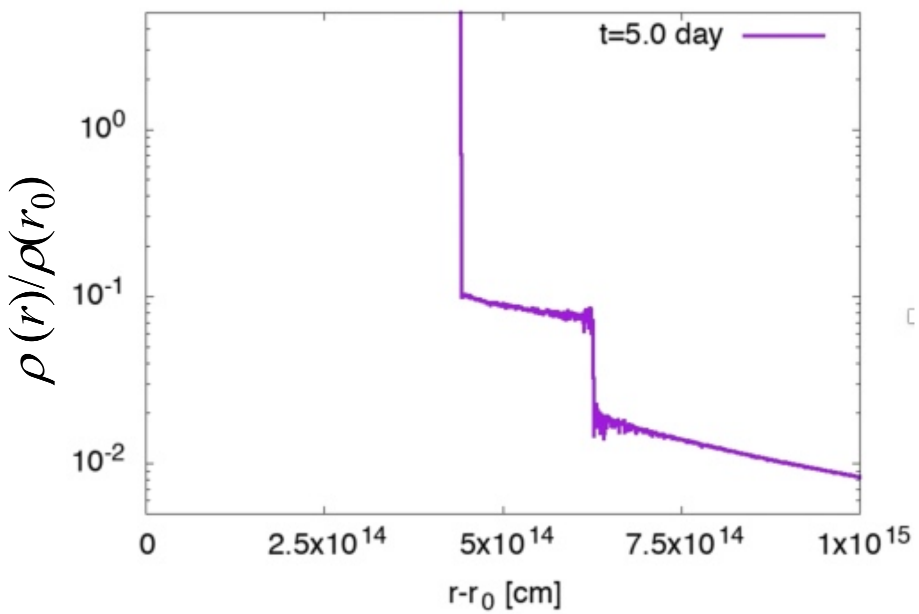
- ✓ Spatial resolution: $\Delta r = \dfrac{2 \times 10^{15}\ \mathrm{cm}}{2 \times 10^{6}\ \mathrm{cells}} \sim 10^9$ cm.

  $\Delta r << \lambda_{\mathrm{bell}} \sim 10^{10}$ cm for fiducial model.

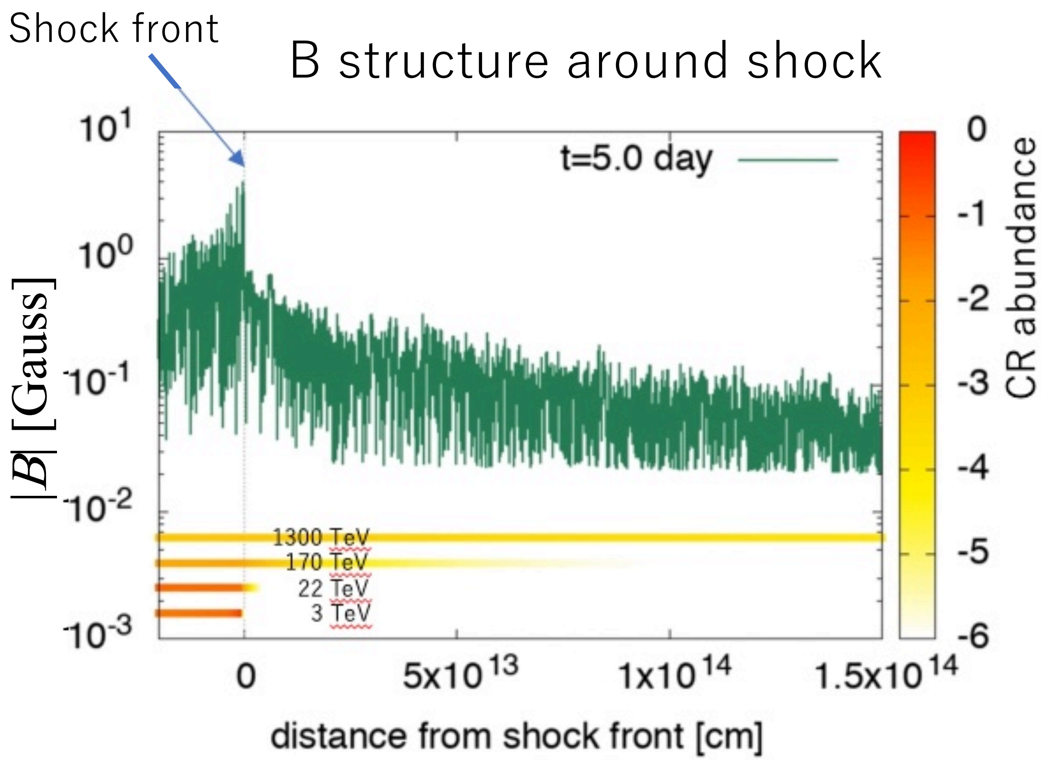
Results: Shock propagation

case: $\dot{M}_{RSG} \sim 10^{-5}$ M_s/yr, $v_{ej} = 10{,}000$ km/s, $\eta = 6 \times 10^{-4}$

density structure



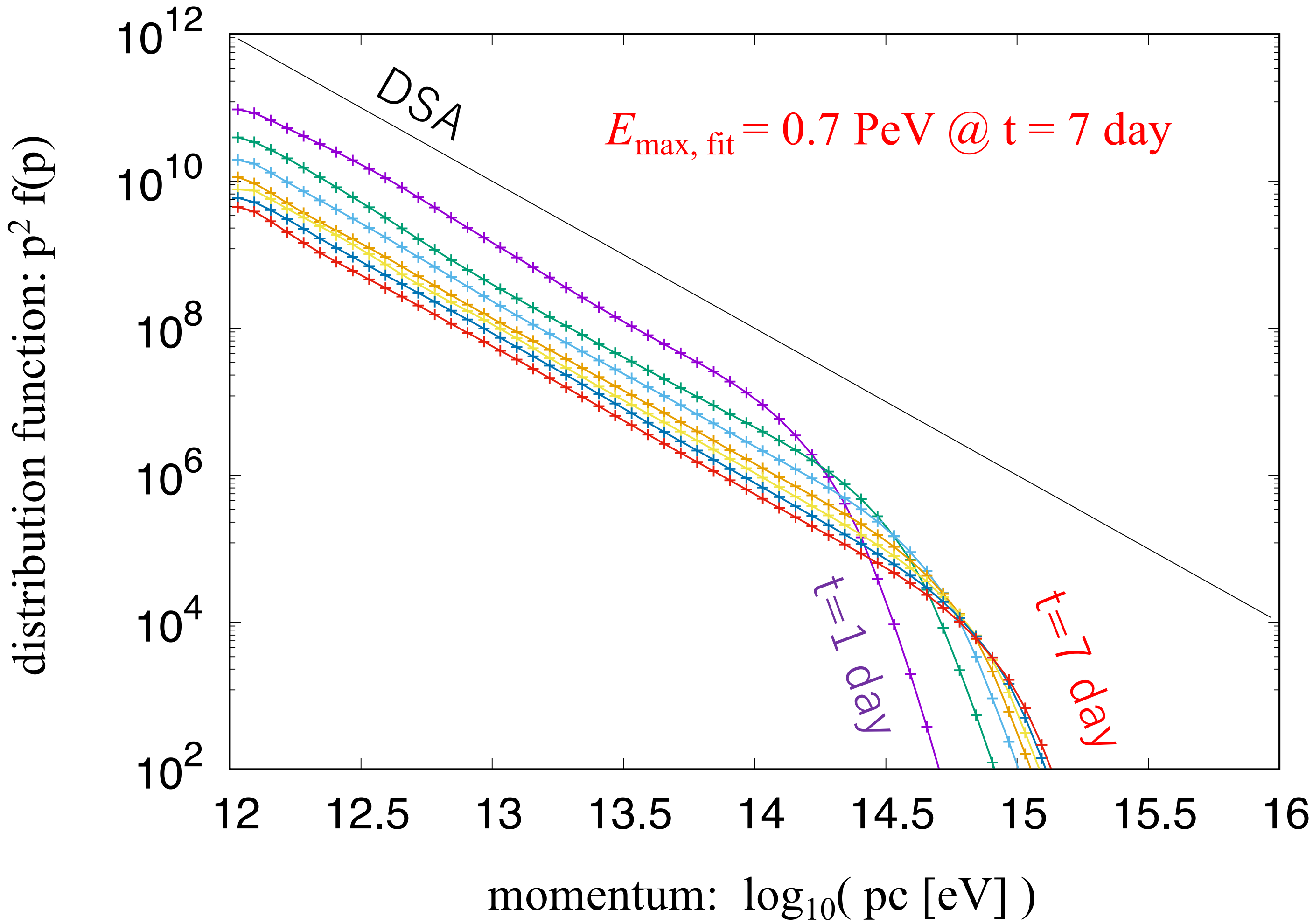
B structure around shock



- ✓ Upstream B-field is indeed amplified by the Bell instability.
- ✓ Degree of the amplification is only factor 10 or less, which is smaller than the Bell instability saturation level: $\frac{B_{sat}}{B_0} = \left(\frac{2\pi\, J\, E_{max}}{e\, c\, {B_0}^2}\right)^{1/2} \sim 100.$

Results: CR spectra at shock

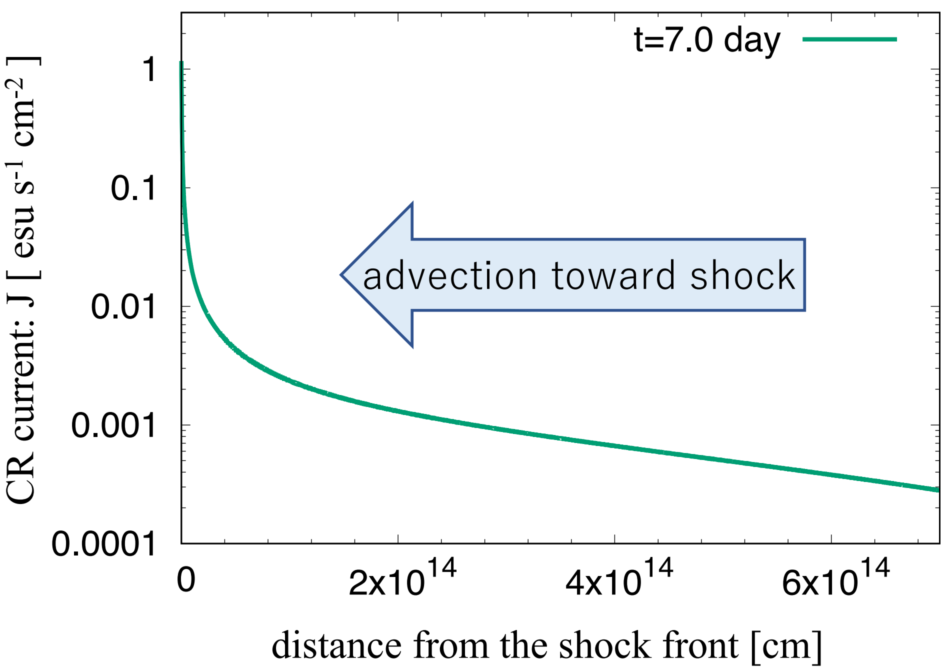
case: $\dot{M}_{RSG} \sim 10^{-5}$ M_s/yr, v_{ej} = 10,000 km/s, $\eta = 6 \times 10^{-4}$

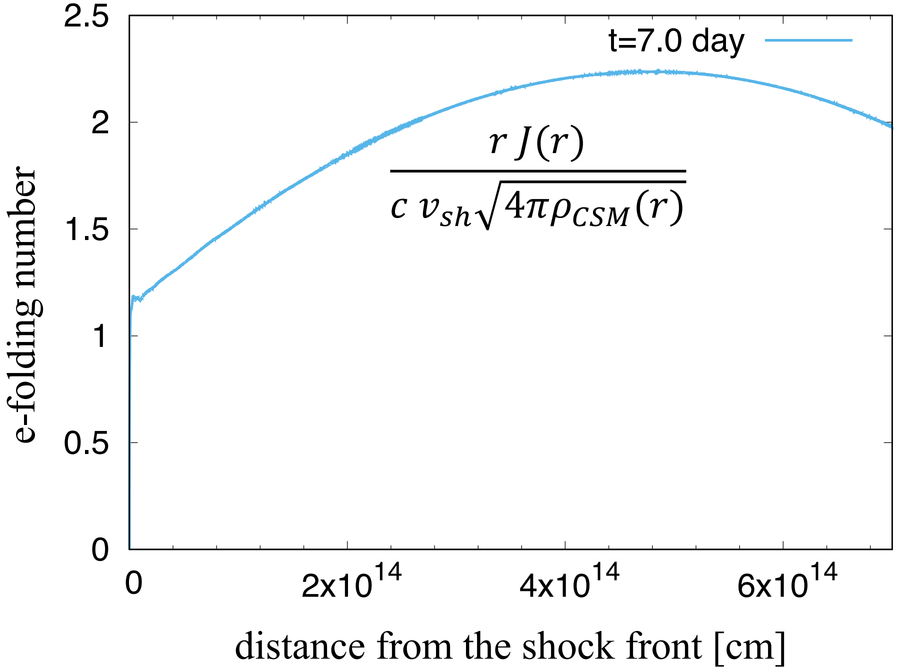


E_{max} marginally reach 1 PeV, but clearly smaller than Knee energy.

Problem: Why non-saturation?

Why B field amplification doesn't reach saturation level.





e-folding number = (advection time)/(growth time)

$$= (r/v_{sh})/t_{Bell} = \frac{r\,J(r)}{c\,v_{sh}\sqrt{4\pi\rho_{CSM}(r)}} \sim 2$$ for fiducial model

expected level of amplification: $\frac{B}{B_0} = e^2 \sim 10$

More Realistic CSM based on Observations

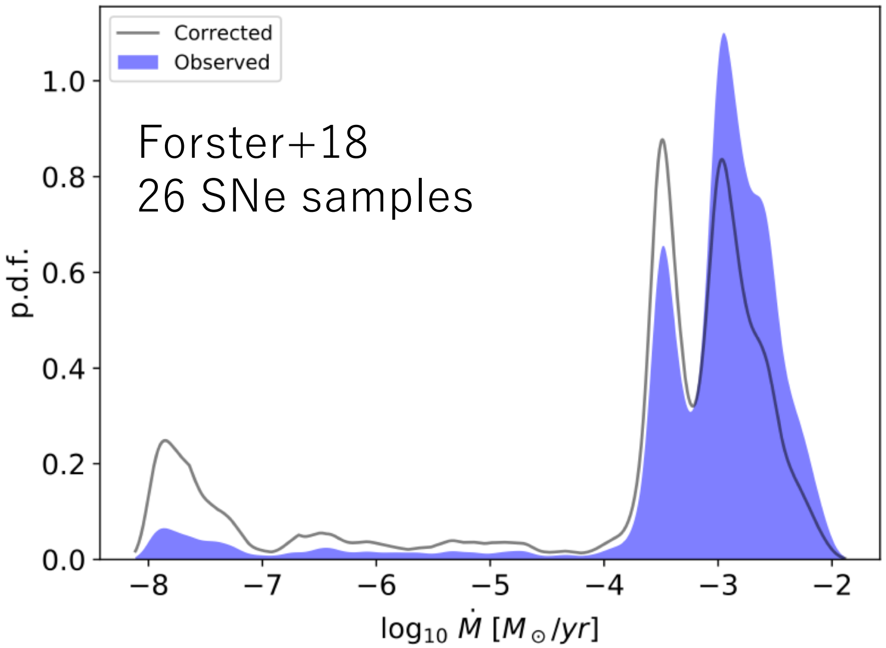
Stellar wind become much more dense before explosion (Forster+18, Nature).

✓ Light curve study of type-II SNe found that stellar wind becomes ~100 times denser than typical RSG wind ($\dot{M} \sim 10^{-3}$ M_s/yr).

→ higher CSM kinetic energy → stronger CSM dynamo → stronger CSM B field

$$B_{\rm CSM} = (8\pi\, \varpi \varepsilon_K)^{1/2} = 2.5\, \varpi^{1/2}\ \mathrm{Gauss} \left(\frac{r}{10^{14} cm}\right)^{-1} \left(\frac{\dot{M}}{10^{-3}\, M_s/yr}\right)^{1/2} \left(\frac{v_w}{10\ km/s}\right)^{1/2}$$

PDF of type-II SNe



Results: Shock propagation

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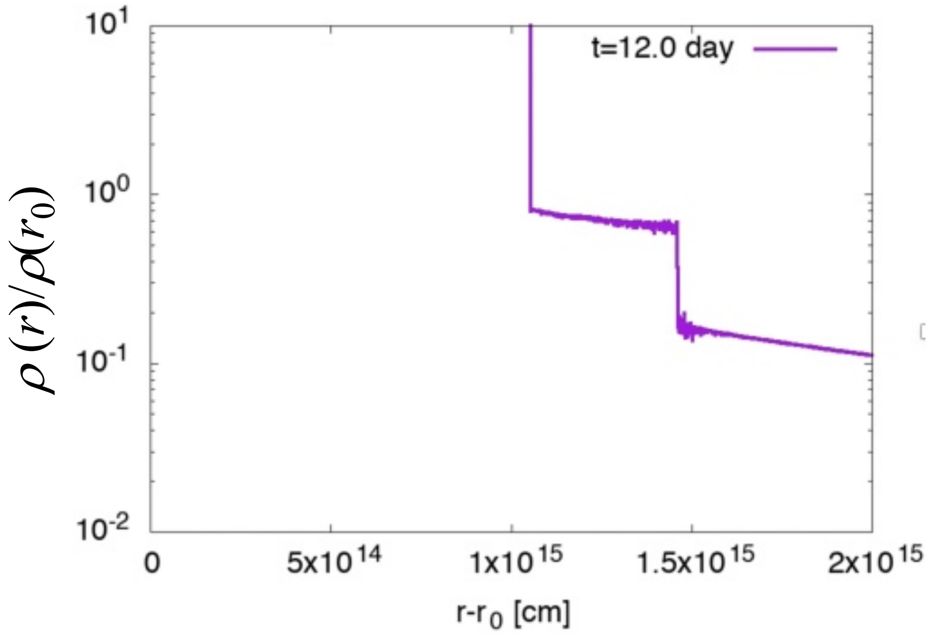
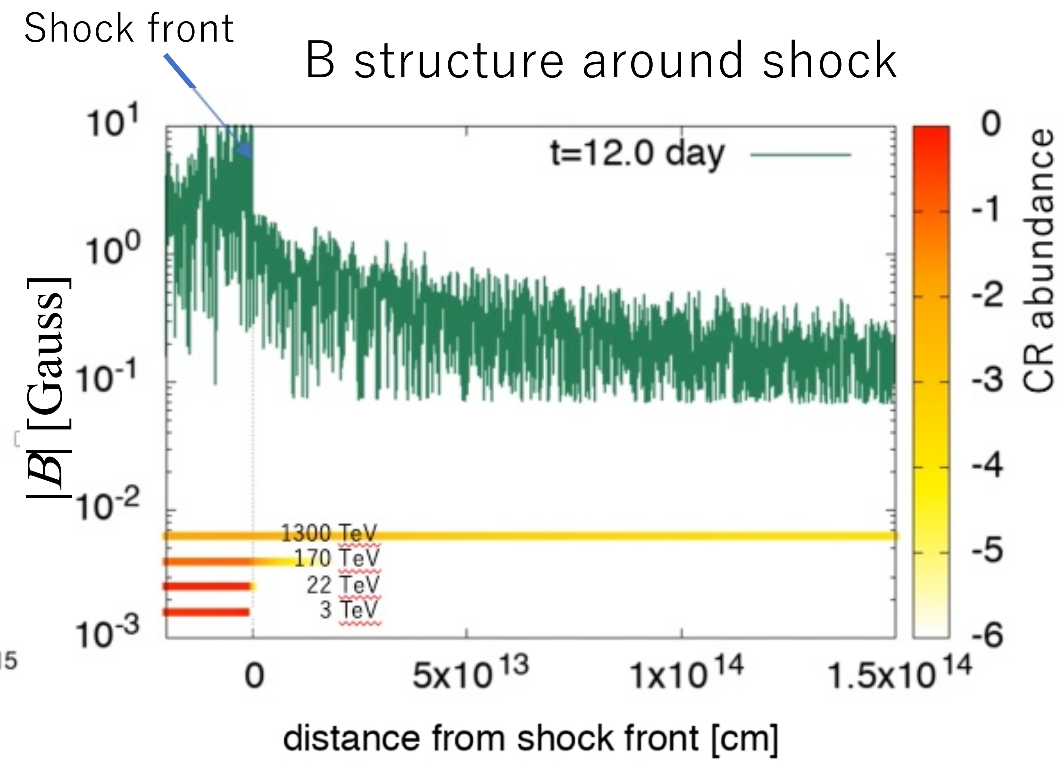
density structure



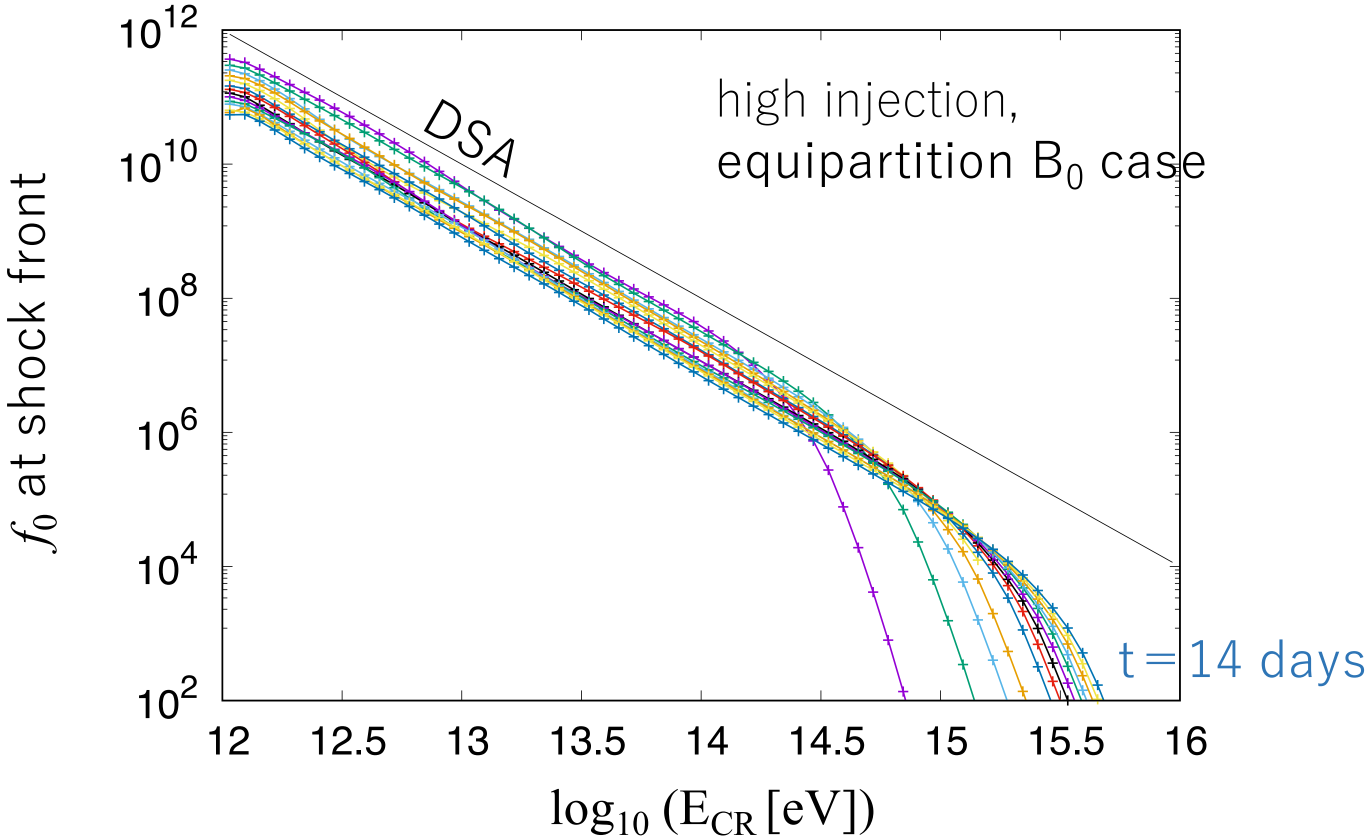
B structure around shock



- ✓ Upstream B-field is amplified by the Bell instability.
- ✓ Degree of the amplification is only factor 10, but the amplified level is enough to make $E_{\max} > 1$ PeV.

higher $\dot{M}$ model (fiducial)

$\dot{M}_{RSG} \sim 10^{-3}$ M_s/yr, $v_{ej} = 10{,}000$ km/s, $\eta = 6 \times 10^{-4}$



$E_{max,\ fit} = 2.9 \times 10^{15}$ eV reaches to the knee energy.

Summary

- ✓ CR acceleration under the influence of the Bell instability is studied.
- ✓ The Bell instability amplifies B field by a factor ~10, but it does not reach to the saturation level because of the limited e-folding number.
- ✓ At very young SNR propagating in RSG CSM, acceleration beyond PeV is possible under the realistic range of parameters.

Future Plan

- ✓ A few more microphysics: CR pressure to fluid.
- ✓ Effects of CR pressure to the background fluid (Kang & Jones 07) would enhances amplification (Drury insta.+dynamo; Beresnyak+09).
- ✓ 3+1D simulation is feasible in near future by FUGAKU supercomputer.
- ✓ Particle acceleration in (mildly) relativistic shocks by GRB/AGN jets can be studied by using similar method.